The Plasma Electrode Pockels Cell for the National Ignition Facility

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Introduction

This article describes the design and prototype testing of a plasma electrode Pockels cell (PEPC) that will be used as part of an optical switch in the laser portion of the National Ignition Facility (NIF). To reduce costs and maximize performance, the laser architecture for NIF is based on a multipass power amplifier. A key component in this laser design is an optical switch that "closes" to trap the optical pulse in an amplifier cavity (for four gain passes) and then "opens," letting the optical pulse escape. This switch includes a Pockels cell that provides voltage control of the laser beam's polarization and a reflecting-transmitting polarizer. Such optical switches are common in many types of lasers, such as Q-switched and regenerative lasers.

The NIF's 40- × 40-cm beam size, its square shape, and its 5-J/cm^2 energy density, however, require using an optical switch of unprecedented size. Conventional Pockels cells that are presently available commercially do not scale to such large apertures or to the square shape required for close packing. Our optical switch is based on a plasma electrode Pockels cell (PEPC) technology that has been proven on the Beamlet laser.[1] In FY98 we finalized a design for the NIF's PEPC and validated it by testing prototypes.

The Plasma Electrode Pockels Cell Design

As has been done with a number of other NIF components, the PEPC is designed as a line replaceable unit (LRU)—the smallest subarray of apertures that will be installed or removed from a NIF beamline. The PEPC LRU is a 4 × 1 module (four apertures high by one aperture wide); an engineering model is shown in Figure 1. Altogether, 48 of these modules, comprised of an operational core mounted in an L-shaped support frame, will be needed to provide optical switching for NIF's 192 beamlines.

The operational part of the PEPC LRU has a midplane sandwiched between a pair of housings, with various other components attached to the housings. The midplane is a glass sheet with four apertures cut out from it. In each aperture, we have potted a 40- × 40- × 1-cm KDP crystal plate with a high-grade silicone rubber. The KDP crystals are electro-optic elements; voltage applied across them controls the PEPC's switching action.

The housings are the main structural element of the PEPC, and their design is the key to its proper operation. A major design feature is to have all the vacuum and electrical interfaces at the top and bottom of the housings. This is critical for achieving the close interbeam spacing required for economical laser construction. The housings are made from Al with a hard-anodized coating, which provides insulation to keep them from shorting out the plasma current. This construction technique is a major departure from the plastic housing used for Beamlet's PEPC.

Other components in the operational core include anodes, cathodes, windows and window retainers, vacuum baffles, plumbing, gauges, and gas flow controllers. The windows are made of fused silica and rest on O-rings. During operation, because the interior of the PEPC is under vacuum, the windows are held in place by atmospheric pressure. However, when the vacuum system is off, the windows are held in place by retainer rings.

The plasma discharges that form the plasma electrodes are produced between sets of anodes and cathodes. These discharges span two full apertures. Each LRU has four cathodes (negative electrodes for the

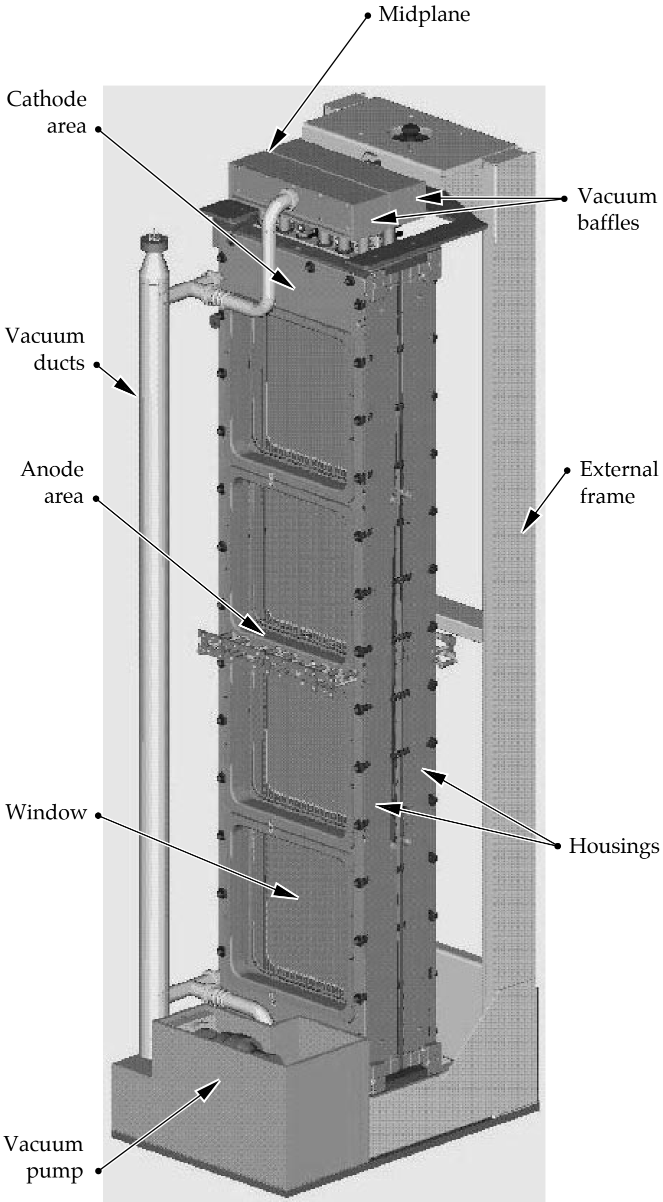

FIGURE 1. Engineering model of the PEPC module for NIF. (08-00-1198-2240pb01)

plasma discharge) mounted within recesses at the top and bottom of the housings. We use planar magnetron cathodes; one for each of the four plasma quadrants. High-field permanent magnets confine the plasmas near the cathode surfaces. This lowers the operating pressure and discharge voltage required and provides good discharge uniformity.

Because cathode sputtering is inevitable and we must control the sputtered material deposited onto optical surfaces, we use cathodes with graphite covers. This assures us that any sputtered material is carbon. Then, by using He mixed with 1% O as an operating gas, the sputtered carbon reacts with the oxygen to produce CO and CO_2. Both of these reaction products are gases, so they are simply pumped away by the vacuum system.

Each discharge also uses a set of six positive electrodes (anodes). During development, we found that segmenting the anodes improved the discharge uniformity by helping to counteract the plasma's natural tendency to pinch. We assure that an equal fraction of the plasma current arrives at each of the anode segments by using appropriate ballast resistors.

The PEPC's vacuum and gas system provides the high-vacuum environment required for producing the plasmas. The vacuum system provides a base pressure of around 5×10^{-5} torr. The working gas is fed in with a feedback-controlled, mass-flow controller. The gas system is set up to maintain a constant operating pressure of 65 mtorr, rather than a constant flow.

The entire PEPC LRU is pumped by a turbomolecular-drag pump, which is backed by a suitable roughing pump. The interior of the housing is pumped through holes in the cathodes. These holes lead to pump-out tubes that penetrate the housing ends and connect to an insulated vacuum baffle, which provides electrical isolation between the two housings when the 17-kV switch-pulses are applied. The baffle prevents plasma electrons from flowing to the grounded vacuum structure during the switching pulses, while still allowing a high vacuum conductance.

Each LRU is driven by a set of pulse generators. Four plasma pulse generators (PPGs) and two switch pulse generators (SPGs) are used, which are not really part of the LRU. In NIF, they will be installed near the LRUs and connected to them by appropriate cables. Each PPG delivers a 1.2-kA current pulse through a plasma channel. Some current is also supplied to conductors that run along the sides of the housing. The current in these conductors produces a magnetic field that helps attract the plasma to the edges of the crystals. The switch pulsers supply a nearly rectangular-shaped, 17-kV, high-voltage pulse across the midplane. The highly conductive plasmas assure that this voltage is uniformly applied across the entire crystal surface.

The external support for mounting the operational portion of the PEPC LRU is an "L" shaped frame. A kinematic mounting system is also attached to this frame. The other side of these mounts will be attached to the NIF periscope structure. At the bottom of the support frame is an interface plate, through which pass all the electrical, gas, cooling, vacuum, diagnostic, and control interfaces.

Prototype Testing and Validation of the NIF PEPC Design

To test and validate our design, we built two prototypes—a "mechanical" prototype (Figure 2) and an "operational" prototype[2] (Figure 3). In this way, we

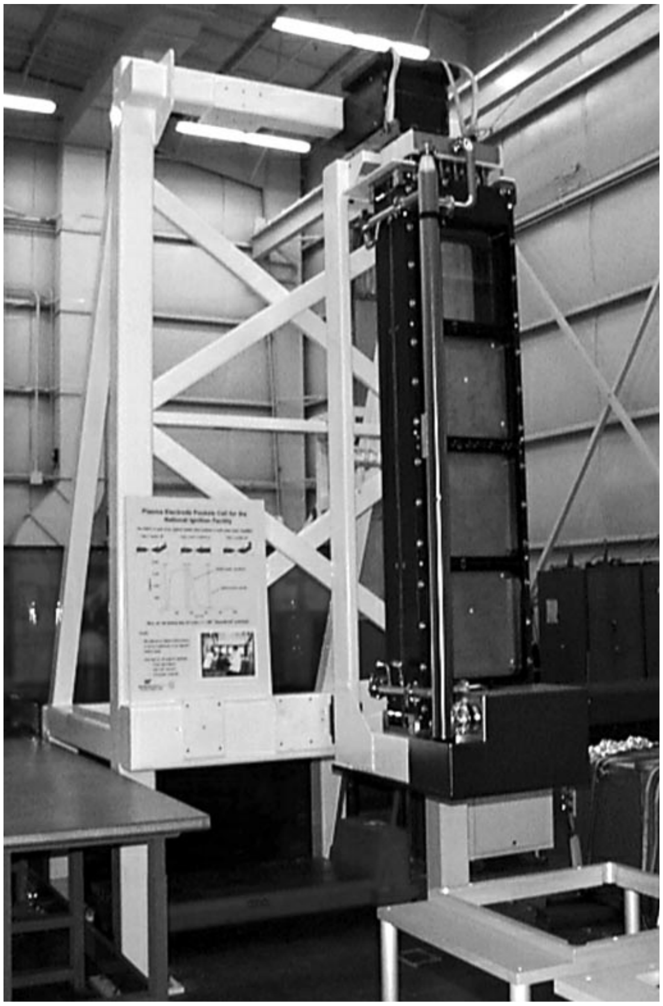

FIGURE 2. The “mechanical” prototype of the NIF PEPC; used to test the external frame design and the kinematic mounts. (08-00-1198-2241pb01)

were able to test the external frame and operational core designs independently and simultaneously.

The mechanical prototype consists of a pair of real PEPC housings with a “dummy” midplane (no KDP) and “dummy” windows (Al and acrylic). The frame is the actual NIF design, as are the kinematic mounts. A vacuum system was included, but no gas system (as of this writing). We used the mechanical prototype for vibration testing and to test other mechanical aspects of the LRU, including its handling, kinematic repeatability, and interfaces.

The mounting repeatability results are excellent. The performance requirement is to reproducibly place the LRU to within ±1 mm. Measurements show that the LRU locates itself to within ±0.025 mm, forty times better than required.

The operational prototype uses a full set of NIF PEPC optics, including eight fused-silica windows and four rapid-growth[3] KDP crystals. These elements will have antireflection (AR) coatings in NIF, but the prototype does not. We know from our Beamlet PEPC experience that the switching performance is not affected by AR-coated optics.

There is no external frame in the operational prototype and, because we do not have sufficient vertical clearance to test it in the vertical NIF orientation, we have to position the assembled housing horizontally. Nevertheless, the prototype allows us to test the actual electro-optic switching operation of the 4 × 1 PEPC.

The 4 × 1 PEPC was evaluated with the apparatus shown schematically in Figure 4. The output coupler of a 10-ns pulsed 1.064-μm laser is relay-imaged with a beam-expanding telescope to the plane of the KDP crystals. The beam is shaped into a square cross section and is also passed through a polarizer to ensure that the PEPC is exposed to linearly polarized light.

We use a system of beam splitters (not shown) to produce four identical full-aperture beams. After passing

FIGURE 3. The “operational” prototype of the NIF PEPC; used to verify full electro-optic operation. (08-00-1198-2242pb01)

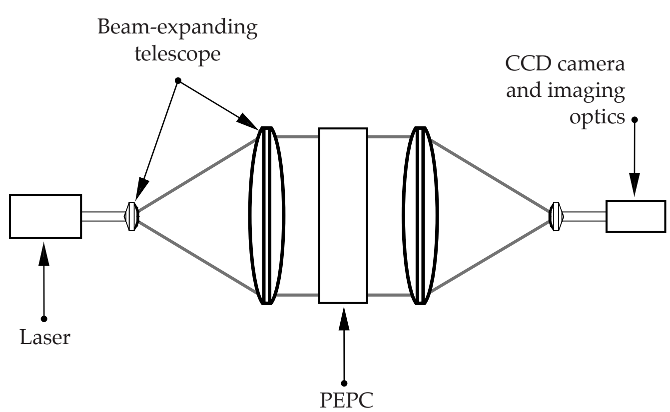

FIGURE 4. A schematic diagram of the optical system used to evaluate the operational prototype. This system allows all four apertures to be simultaneously tested. (08-00-1198-2243pb01)

through the cell and an analyzing polarizer, the four beams are each relay-imaged to a CCD camera. We determined the PEPC's performance by measuring the extinction ratio (ER). We did this by comparing the CCD image with and without the PEPC operating. The NIF requirements are that the average ER for each aperture must be greater than 100, while the worst spot can have an ER no lower than 50.

When the ER is 100, 99% of the light is in the proper polarization; an ER of 50 corresponds to having 98% of the light correctly polarized. Put another way, if the ER is 50 on some part of the aperture, a 2% amplitude modulation is introduced into the beam.

In NIF, shaped optical pulses of up to 20 ns in duration pass through the PEPC four times on a normal shot. The temporal relationship among these four passes and the switch-pulse is shown in Figure 5.

To fully validate the operation, we must measure the performance at each of the four times. Pass One occurs before the switch-pulse starts and the ER averages more than 1000 for each aperture. The minimum ER for each aperture is about 200, easily meeting the NIF requirement. The results for Pass Three are shown in Figure 6. Here, the PEPC is rotating the beam polarization by 90°. This corresponds to a cavity-closed condition. The average and minimum ERs all easily meet the NIF requirements. The data for Pass-Two timing are indistinguishable from the Pass-Three results. In fact, we have to advance the optical pulse more than 160 ns before we notice a significant reduction in the ER. Finally, the results for Pass Four, or the switch-out timing, are shown in Figure 7. Again, the average and minimum ERs easily meet the NIF requirement.

These results are not isolated "best results" data. The PEPC system fires every four seconds in the lab and the shot-to-shot results are very reproducible. We have taken series of 100 shots and found the ER variation to be less than 10%. After prolonged use (over 20 minutes of continuous firing), we see a slight degradation in the ER due to the heating up of the KDP crystals from the discharges.

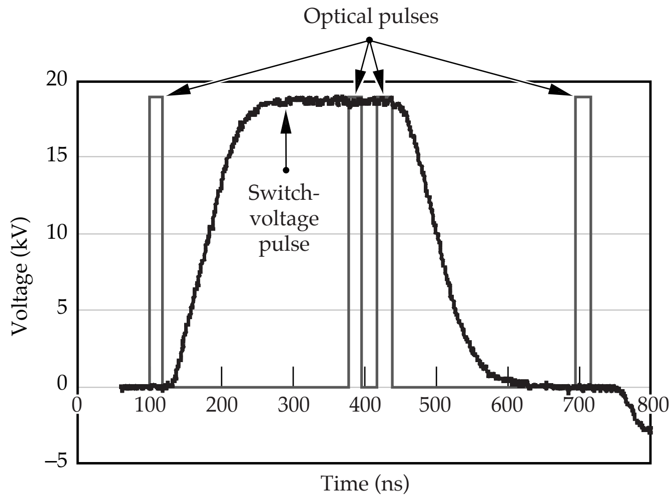

FIGURE 5. Diagram showing the temporal relationship between the voltage pulse applied to the PEPC and the four-times-per-NIF-shot optical pulse that traverses the PEPC. (08-00-1198-2244pb01)

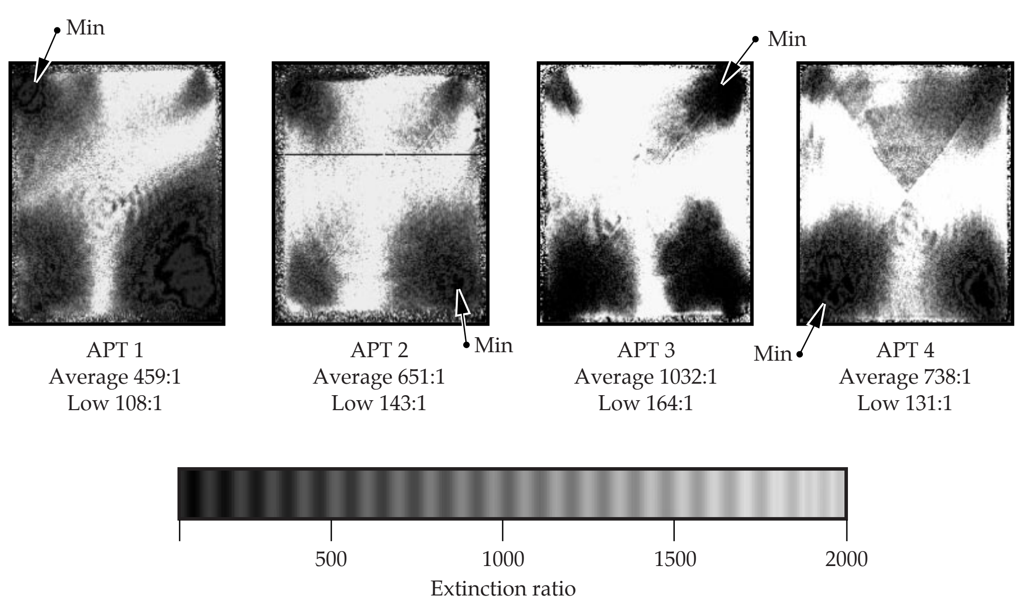

FIGURE 6. Optical data for Pass-Three timing after the voltage pulse has been applied to the cell; the amplifier cavity is "closed." The Pass-Three ERs for all four apertures (APT 1, 2, 3, 4) are much better than the NIF requirements. (08-00-1198-2245pb01)

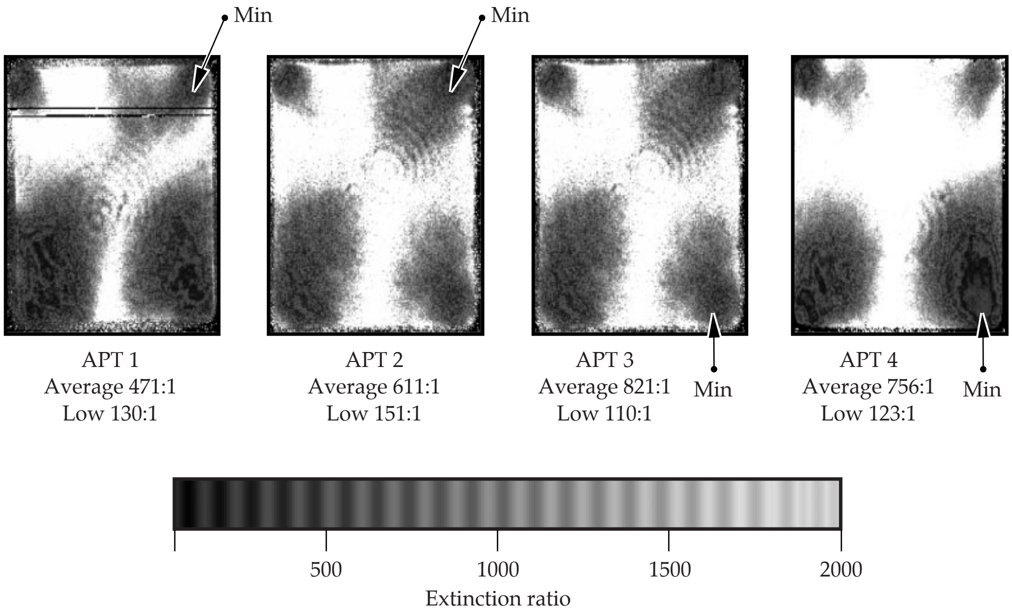

FIGURE 7. Optical data for Pass-Four timing after the voltage pulse to the cell has ended; the amplifier cavity at this time will be "open." The high-energy laser pulse will now be switched out of the amplifier cavity. The Pass-Four ERs for all four apertures (APT 1, 2, 3, 4) are much better than the NIF requirements.
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Conclusion

We have designed a four-aperture plasma electrode Pockels cell for use in the NIF. This device is the active part of a successful optical switch for a multipass laser amplifier design. We have proven the optical performance of our design by building and operating a full-size operational prototype. Furthermore, the mechanical aspects of our design have been simultaneously proven with a mechanical prototype containing no active optical elements. Both the optical performance and the kinematic mounting system for locating the entire structure meet or exceed the NIF requirements by wide margins.

Notes and References

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2. M. A. Rhodes, S. Fochs, and C. D. Boley, "Plasma Pockels Cell Based Optical Switch for the National Ignition Facility," *International Conference on Plasma Science*, San Diego, CA, May 19–22, 1997.
3. N. P. Zaitseva, J. J. De Yoreo, M. R. Dehaven, R. L. Vital, K. E. Montgomery, M. Richardson, and L. J. Atherton, *J. Cryst. Growth* **180**, 255 (1997).